Partonic substructure of nucleons and nuclei with dimuon production

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Abstract. Dimuon production has been studied in a series of fixed-target experiments at Fermilab during the last two decades. Highlights from these experiments, together with recent results from the Fermilab E866 experiment, are presented. Future prospects for studying the parton distributions in the nucleons and nuclei using dimuon production are also discussed.

Keywords: Drell-Yan, quarkonium production, parton distributions
PACS: 13.85.Qk, 14.20.Dh, 24.85.+p, 13.88.+e

INTRODUCTION

During the last two decades, a series of fixed-target dimuon production experiments (E772, E789, E866) have been carried out using 800 GeV/c proton beam at Fermilab. At 800 GeV/c, the dimuon data contain Drell-Yan continuum as well as quarkonium productions (J/Ψ, Ψ', and Υ resonances). The Drell-Yan process and quarkonium productions often provide complementary information, since Drell-Yan is an electromagnetic process involving quark-antiquark annihilation while the quarkonium production is a strong interaction process dominated by gluon-gluon fusion at this beam energy.

The Fermilab dimuon experiments covers a broad range of physics topics. The Drell-Yan data have provided information on the antiquark distributions in the nucleons [1, 2] and nuclei [3, 4]. These results showed the surprising results that the antiquark distributions in the nuclei are not enhanced [3, 4], contrary to the expectation of models which predict nuclear enhancement of meson clouds. Later, the measurement of the Drell-Yan cross section ratios $p+d/p+p$ clearly established the flavor asymmetry of the $\bar{d}$ and $\bar{u}$ distributions in the proton, and the x-dependence of this asymmetry was determined [2]. Pronounced nuclear dependences of quarkonium productions were observed for J/Ψ, Ψ', and Υ resonances [5, 6]. The nuclear dependence of Drell-Yan cross sections has also provided information on the energy loss of quarks traversing the nucleus [4, 7]. In addition, the decay angular distributions for Drell-Yan [8, 9], J/Ψ [10], and Υ resonances [11] have been measured.

In this article we first discuss the subject of the flavor structure of the sea quark distributions in the nucleons. The observation of a striking flavor asymmetry of the nucleon sea, inspired by the seminal work of Tony Thomas [12], has profound implications on our current knowledge on the parton substructures in the nucleons. Some recent results from the dimuon production experiments are then presented. Finally, prospects for future experiments to study flavor structures of the nucleons and nuclei will be discussed.

FLAVOR STRUCTURE OF LIGHT-QUARK SEA

The earliest parton models assumed that the proton sea was flavor symmetric, even though the valence quark distributions are clearly flavor asymmetric. The similar masses for the up and down quarks suggest that the nucleon sea should be nearly up-down symmetric. The issue of the equality of $\bar{u}$ and $\bar{d}$ was first encountered in the Gottfried integral [13], given as

$$I_G = \int_0^1 \left[F_2^p(x) - F_2^n(x)\right]/x\,dx = \frac{1}{3} + \frac{2}{3}\int_0^1 \left[\bar{u}_p(x) - \bar{d}_p(x)\right] dx, \tag{1}$$

where F_2^p and F_2^n are the proton and neutron structure functions. Under the assumption of a $\bar{u}$, $\bar{d}$ flavor-symmetric sea in the nucleon, the Gottfried Sum Rule [13], $I_G = 1/3$, is obtained. The most accurate measurement [14] of the Gottfried integral gives 0.235 ± 0.026, significantly below 1/3. This surprising result has generated much interest. It is remarkable that, already in 1983, Tony Thomas predicted a large excess of $\bar{d}$ to $\bar{u}$ as a direct evidence for a pionic component in the nucleon. In his paper [12], Tony commented on “the lack of experimental information about the shapes of $s(x)$, $\bar{s}(x)$ and $\bar{d}(x) - \bar{u}(x)$”, and concluded his paper “with a plea for better measurements of these three quantities in the free proton”.

The shape of the $\bar{d}(x) - \bar{u}(x)$ was later measured in proton-induced Drell-Yan and semi-inclusive DIS experiments. At Fermilab, the E866/NuSea [2] Collaboration measured the DY cross section ratios for $p+d$ to that of $p+p$:

$$\sigma_{DY}(p+d)/2\sigma_{DY}(p+p) \simeq \left[1 + \bar{d}(x)/\bar{u}(x)\right]/2. \tag{2}$$

This ratio was found to be significantly different from unity for $0.015 < x < 0.35$, showing an excess of $\bar{d}$ to $\bar{u}$ over an appreciable range in x.

Many theoretical models, including meson-cloud model, chiral-quark model, Pauli-blocking model, instanton model, chiral-quark soliton model, and statistical model, have been proposed to explain the $\bar{d}/\bar{u}$ asymmetry. Details of these various models can be found in some review articles [15, 16]. These models also have specific predictions for the spin structure of the nucleon sea [17]. In the meson-cloud model, for example, a quark would undergo a spin flip upon an emission of a pseudoscalar meson ($u^\uparrow \to \pi^\circ(u\bar{u}, d\bar{d}) + u^\downarrow$, $u^\uparrow \to \pi^+(u\bar{d}) + d^\downarrow$, $u^\uparrow \to K^+ + s^\downarrow$, etc.). The antiquarks ($\bar{u}, \bar{d}, \bar{s}$) are unpolarized ($\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s} = 0$) since they reside in spin-0 mesons. The strange quarks (s), on the other hand, would have a negative polarization since the up valence quarks in the proton are positively polarized and the $u^\uparrow \to K^+ + s^\downarrow$ process would lead to an excess of $s^\downarrow$. By considering a vector meson (ρ) cloud, non-zero $\bar{u}, \bar{d}$ sea quark polarizations with $\Delta\bar{d} - \Delta\bar{u} > 0$ were predicted [18, 19].

The Pauli-blocking model [20] predicts that an excess of $q^\uparrow(q^\downarrow)$ valence quarks would inhibit the creation of a pair of $q^\uparrow\bar{q}^\downarrow$ ($q^\downarrow\bar{q}^\uparrow$) sea quarks. Since the polarization of the $u(d)$ valence quarks is positive (negative), this model predicts a positive (negative) polarization for the $\bar{u}(\bar{d})$ sea ($\Delta\bar{u} > 0 > \Delta\bar{d}$).

In the instanton model [21], the quark sea can result from a scattering of a valence quark off a nonperturbative vacuum fluctuation of the gluon field, instanton. The correlation between the sea quark helicity and the valence quark helicity in the ’t Hooft

effective lagrangian (i.e. $u^{\uparrow}$ leads to a $\bar{d}^{\downarrow}$) naturally predicts a positively (negatively) polarized $\bar{u}(\bar{d})$ sea. In particular, this model predicts [22] a large $\Delta\bar{u}, \Delta\bar{d}$ flavor asymmetry with $\Delta\bar{u} > \Delta\bar{d}$, namely, $\int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx = \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx$.

In the chiral-quark soliton model [23, 24], the polarized isovector distributions $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ appears in leading-order (N_c^2) in a $1/N_c$ expansion, while the unpolarized isovector distributions $\bar{u}(x) - \bar{d}(x)$ appear in next-to-leading order (N_c). Therefore, this model predicts a large flavor asymmetry for the polarized sea $[\Delta\bar{u}(x) - \Delta\bar{d}(x)] > [\bar{d}(x) - \bar{u}(x)]$.

In the statistical model [25], the momentum distributions for quarks and antiquarks follow a Fermi-Dirac distributions function characterized by a common temperature and a chemical potential μ which depends on the flavor and helicity of the quarks. It can be shown that $\mu_{\bar{q}\uparrow} = -\mu_{q\downarrow}$ and $\mu_{\bar{q}\downarrow} = -\mu_{q\uparrow}$. Together with the constraints of the valence quark sum rules and inputs from polarized DIS experiments, this model leads to the prediction that $\bar{d} > \bar{u}$ and $\Delta\bar{u} > 0 > \Delta\bar{d}$.

Measurements of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ are clearly of great current interest. Both the HERMES [26] and the COMPASS [27] collaborations have reported results on the extraction of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ from polarized semi-inclusive DIS data. These results show that $\Delta\bar{u}$, $\Delta\bar{d}$ are small, but with large uncertainties. A recent global analysis [28] of polarized DIS and polarized $p-p$ interaction indicates that $\Delta\bar{u}(x) > 0$, $\Delta\bar{d}(x) < 0$, and $|\Delta\bar{u}(x)| < |\Delta\bar{d}(x)|$. This interesting result suggests that the sea-quark polarization is flavor-asymmetric and of opposite sign compared to the unpolarized case. Additional data are anticipated for W-boson production at RHIC [29]. The longitudinal single-spin asymmetry for W production in polarized $p+p$ collision is sensitive to $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$.

While various theoretical models can describe the general trend of the $\bar{d}/\bar{u}$ asymmetry, they all have difficulties [30, 31] explaining the Fermilab E866 data at large x ($x > 0.2$), where $\bar{d}/\bar{u}$ drops below 1. However, the E866 large-x data suffer from large statistical uncertainties, and more precise measurements are needed. The 120 GeV Main Injector at Fermilab and the new 30-50 GeV proton accelerator, J-PARC, present opportunities for extending the $\bar{d}/\bar{u}$ measurement to larger x ($0.25 < x < 0.7$). For given values of x_1 and x_2 the DY cross section is proportional to $1/s$, hence the DY cross section at these lower energies are significantly larger than at 800 GeV. A definitive measurement of the $\bar{d}/\bar{u}$ over the region $0.25 < x < 0.7$ could be obtained for an upcoming experiment E906 [32] at Fermilab and a proposed measurement [33] at J-PARC.

To disentangle the $\bar{d}/\bar{u}$ asymmetry from the possible charge-symmetry violation effect [34], one could consider W boson production in $p+p$ collision at RHIC. The ratio of the $p+p \to W^+ + X$ and $p+p \to W^- + X$ cross sections is sensitive to $\bar{d}/\bar{u}$. An important feature of the W production asymmetry in $p+p$ collision is that it is completely free from the assumption of charge symmetry [35]. Another advantage is that it is free from any nuclear effects. Moreover, the W production is sensitive to $\bar{d}/\bar{u}$ flavor asymmetry at a Q^2 scale of $\sim 6500\ \mathrm{GeV}^2/\mathrm{c}^2$, significantly larger than all existing measurements. This offers the opportunity to examine the QCD evolution of the sea-quark flavor asymmetry. A recent study showed that W asymmetry measurements at RHIC could provide an independent determination of $\bar{d}/\bar{u}$ [36].

While it is generally assumed that the gluon distributions in the proton and neutron are identical, this assumption has not been tested experimentally. A possible mechanism

for generating different gluon distributions in the proton and neutron, as pointed out by Piller and Thomas [37], is the violation of charge symmetry in the parton distributions in the nucleons [35]. Unlike the electromagnetic Drell-Yan process, quarkonium production is a strong interaction dominated by the subprocess of gluon-gluon fusion at 800 GeV beam energy. Therefore, the Υ production ratio, $\sigma(p+d \to \Upsilon)/\sigma(p+p \to \Upsilon)$, is expected to probe the gluon content in the neutron relative to that in the proton [38]. The $\sigma(p+d)/2\sigma(p+p)$ ratios for Υ production with 800 GeV proton beam have been reported recently [38], and they are consistent with unity, in striking contrast to the corresponding values for the Drell-Yan process. The Υ data indicate that the gluon distributions in the proton and neutron are very similar. These results are consistent with no charge symmetry breaking effect in the gluon distributions.

TRANSVERSE SPIN AND DRELL-YAN PROCESS

The study of the transverse momentum dependent (TMD) parton distributions of the nucleon has received much attention in recent years as it provides new perspectives on the hadron structure and QCD [39]. These novel TMDs can be extracted from semi-inclusive deep-inelastic scattering (SIDIS) experiments. Recent measurements of the SIDIS by the HERMES [40] and COMPASS [41] collaborations have shown clear evidence for the existence of the T-odd Sivers functions. These data also allow the first determination [42] of the magnitude and flavor structure of the Sivers functions and the nucleon transversity distributions.

The TMD and transversity parton distributions can also be probed in Drell-Yan experiments. As pointed out [43] long time ago, the double transverse spin asymmetry in polarized Drell-Yan, A_{TT}, is proportional to the product of transversity distributions, $h_1(x_q)h_1(x_{\bar{q}})$. The single transverse spin asymmetry, A_N, is sensitive to the Sivers function [44], $f_{1T}^{\perp}(x)$ of the polarized proton (beam or target). Even unpolarized Drell-Yan experiments can be used to probe the TMD distribution function, since the $\cos 2\phi$ azimuthal angular dependence is proportional to the product of two Boer-Mulders functions [45], $h_1^{\perp}(x_1)h_1^{\perp}(x_2)$. A unique feature of the Drell-Yan process is that, unlike the SIDIS, no fragmentation functions are involved. Therefore, the Drell-Yan process provides an entirely independent technique for measuring the TMD functions. Furthermore, the proton-induced Drell-Yan process is sensitive to the sea-quark TMDs and can lead to flavor separation of TMDs when combined with the SIDIS data. Finally, the intriguing prediction [46] that the T-odd TMDs extracted from DIS will have a sign-change for the Drell-Yan process remains to be tested experimentally.

No polarized Drell-Yan experiments have yet been performed. However, some information on the Boer-Mulders functions have been extracted recently from the azimuthal angular distributions in the unpolarized Drell-Yan process. The general expression for the Drell-Yan angular distribution is [47]

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi, \tag{3}$$

where θ and ϕ are the polar and azimuthal decay angle of the l^+ in the dilepton rest frame. Boer showed that the $\cos 2\phi$ term is proportional to the convolution of the quark

and antiquark Boer-Mulders functions in the projectile and target [48]. This can be understood by noting that the Drell-Yan cross section depends on the transverse spins of the annihilating quark and antiquark. Therefore, a correlation between the transverse spin and the transverse momentum of the quark, as represented by the Boer-Mulders function, would lead to a preferred transverse momentum direction.

Pronounced $\cos 2\phi$ dependences were indeed observed in the NA10 [49] and E615 [50] pion-induced Drell-Yan experiments, and attributed to the Boer-Mulders function. The first measurement of the $\cos 2\phi$ dependence of the proton-induced Drell-Yan process was recently reported for $p+p$ and $p+d$ interactions at 800 GeV/c [9]. In contrast to pion-induced Drell-Yan, significantly smaller (but non-zero) $\cos 2\phi$ azimuthal angular dependence was observed in the $p+p$ and $p+d$ reactions. While the pion-induced Drell-Yan process is dominated by annihilation between a valence antiquark in the pion and a valence quark in the nucleon, the proton-induced Drell-Yan process involves a valence quark in the proton annihilating with a sea antiquark in the nucleon. Therefore, the $p+p$ and $p+d$ results suggest [9, 51] that the Boer-Mulders functions for sea antiquarks are significantly smaller than those for valence quarks.

FUTURE PROSPECTS AT FERMILAB AND J-PARC

Future fixed-target dimuon experiments have been proposed at the 120 GeV Fermilab Main Injector and the 50 GeV J-PARC facilities. As discussed earlier, the Fermilab E906 experiment will extend the $\bar{d}/\bar{u}$ asymmetry measurement to larger x region. Another goal of this experiment is to determine the antiquark distributions in nuclei at large x using nuclear targets. New information on the quark energy loss in nuclei is also expected. An advantage of lower beam energies is that a much more sensitive study of the partonic energy loss in nuclei could be carried out using the Drell-Yan nuclear dependence [7].

With the possibility to accelerate polarized proton beams at J-PARC [52], the spin structure of the proton can also be investigated with the proposed dimuon experiments. In particular, polarized Drell-Yan process with polarized beam and/or polarized target at J-PARC would allow a unique program on spin physics complementary to polarized DIS experiments and the RHIC-Spin programs. Specific physics topics include the measurements of T-odd Boer-Mulders distribution function in unpolarized Drell-Yan, the extraction of T-odd Sivers distribution functions in singly transversely polarized Drell-Yan, the helicity distribution of antiqaurks in doubly longitudinally polarized Drell-Yan, and the transversity distribution in doubly transversely polarized Drell-Yan. It is worth noting that polarized Drell-Yan is one of the major physics program at the GSI Polarized Antiproton Experiment (PAX). The RHIC-Spin program will likely provide the first results on polarized Drell-Yan. However, the high luminosity and the broad kinematic coverage for the large-x region at J-PARC would allow some unique measurements to be performed in the J-PARC dimuon experiments.

REFERENCES

1. P.L. McGaughey *et al.*, Phys. Rev. Lett. **69**, 1726 (1992).

2. E.A. Hawker *et al.*, Phys. Rev. Lett. **80**, 3715 (1998); J.C. Peng *et al.*, Phys. Rev. D **58**, 092004 (1998); R.S. Towell *et al.*, Phys. Rev. D **64**, 052002 (2001).
3. D.M. Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).
4. M.A. Vasiliev *et al.*, Phys. Rev. Lett. **83**, 2304 (1999).
5. D.M. Alde *et al.*, Phys. Rev. Lett. **66**, 133 (1991); **66**, 2285 (1991).
6. M.J. Leitch *et al.*, Phys. Rev. D **52**, 4251 (1995).
7. G.T. Garvey and J.C. Peng, Phys. Rev. Lett. **90**, 092302 (2003).
8. P.L. McGaughey, J.M. Moss, and J.C. Peng, Annu. Rev. Nucl. Part. Sci. **49**, 217 (1999).
9. L.Y. Zhu *et al.*, Phys. Rev. Lett. **99**, 082301 (2007); **102**, 182001 (2009).
10. T.H. Chang *et al.*, Phys. Rev. Lett. **91**, 211801 (2003).
11. C.N. Brown *et al.*, Phys. Rev. Lett. **86**, 2529 (2001).
12. A. W. Thomas, Phys. Lett. B **126**, 97 (1983).
13. K. Gottfried, Phys. Rev. Lett. **18**, 1174 (1967).
14. P. Amaudruz *et al.*, Phys. Rev. Lett. **66**, 2712 (1991).
15. S. Kumano, Phys. Rep. **303**, 183 (1998).
16. G.T. Garvey and J.C. Peng, Prog. Part. Nucl. Phys. **47**, 203 (2001).
17. J.C. Peng, Eur. Phys. J. A **18**, 395 (2003).
18. R. J. Fries and A. Schäfer, Phys. Lett. B **443**, 40 (1998).
19. F. G. Cao and A. I. Signal, Eur. Phys. J. C **21**, 105 (2001).
20. A.W. Schreiber, A.I. Signal, and A.W. Thomas, Phys. Rev. D **44**, 2653 (1991); F.M. Steffens and A.W. Thomas, Phys. Rev. C **55**, 900 (1997).
21. A.E. Dorokhov and N.I. Kochelev, Phys. Lett. B **259**, 335 (1991); **304**, 167 (1993).
22. A. Dorokhov, hep-ph/0112332.
23. D. I. Diakonov *et al.*, Nucl. Phys. B **480**, 341 (1996).
24. M. Wakamatsu and T. Kubota, Phys. Rev. D **57**, 5755 (1998).
25. C. Bourrely, J. Soffer and F. Buccella, Eur. Phys. J. C **23**, 487 (2002).
26. A. Airapetian *et al.*, Phys. Rev. D **71**, 012003 (2005); Phys. Rev. Lett. **92**, 012005 (2004).
27. A. Korzenev, arXiv:0909.3729.
28. D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Phys. Rev. D **80**, 034030 (2009).
29. G. Bunce, N. Saito, J. Soffer and W. Vogelsang, Ann. Rev. Nucl. Part. Sci. **50**, 525 (2000).
30. W.P. Hwang, J. Speth and G.E. Brown, Z. Phys. A **339**, 383 (1991).
31. W. Melnitchouk, J. Speth and A.W. Thomas, Phys. Rev. D **59** 014033 (1999).
32. http://www.phy.anl.gov/mep/drell-yan; D. Geesaman, P. Reimer, *et al.*, Fermilab E906 (1999).
33. http://j-parc.jp/NuclPart/pac_0606/pdf/p04-Peng.pdf; J.C. Peng, S. Sawada, *et al.*, J-PARC Proposal P04 (2006).
34. B.Q. Ma, Phys. Lett. B **274**, 111 (1992).
35. T. Londergan, J.C. Peng, and A.W. Thomas, arXiv:0907.2352.
36. R. Yang, J.C. Peng and M. Grosse-Perdekamp, Phys. Lett. B **680**, 231 (2009).
37. G. Piller and A.W. Thomas, Z. Phys. C **70**, 661 (1996).
38. L.Y. Zhu *et al.*, Phys. Rev. Lett. **100**, 062301 (2008).
39. V. Barone, A. Drago, and P. G. Ratcliffe, Phys. Rep. **359**, 1 (2002).
40. A. Airapetian *et al.*, Phys. Rev. Lett. **94**, 012002 (2005); **101**, 152002 (2009).
41. V. Yu. Alexakhin *et al.*, Phys. Rev. Lett. **94**, 202002 (2005); M. Alekseev *et al.*, Phys. Lett. B **673**, 127 (2009).
42. W. Vogelsang and F. Yuan, Phys. Rev. D **72**, 054028 (2005); M. Anselmino *et al.*, Phys. Rev. D **72**, 094007 (2005); M. Anselmino *et al.*, Eur. Phys. J. **A39**, 89 (2009).
43. J.P. Ralston and D.E. Soper, Nucl. Phys. B **152**, 109 (1979).
44. D. Sivers, Phys. Rev. D **41**, 83 (1990).
45. D. Boer and P.J. Mulders, Phys. Rev. D **57**, 5780 (1998).
46. J.C. Collins, Phys. Lett. B **536**, 43 (2002).
47. C.S. Lam and W.K. Tung, Phys. Rev. D **18**, 2447 (1978).
48. D. Boer, Phys. Rev. D **60**, 014012 (1999).
49. S. Falciano *et al.*, Z. Phys. C **31**, 513 (1986).
50. J.S. Conway *et al.*, Phys. Rev. D **39**, 92 (1989); J.G. Heinrich *et al.*, Phys. Rev. D **44**, 1909 (1991).
51. B. Zhang, Z. Lu, B.-Q. Ma, and I. Schmidt, Phys. Rev. D **77**, 054011 (2008).
52. http://j-parc.jp/NuclPart/pac_0801/pdf/Goto.pdf; Y. Goto, *et al.*, J-PARC Proposal P24 (2007).